Boussinesq Modeling of Alongshore Swash Zone Currents

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LONG-TERM GOALS

The long-term goal of the study is to develop and integrate numerical models for the understanding and prediction of nearshore processes. The focus of the project is to develop the capability of modeling alongshore swash currents under field conditions based on Boussinesq-type formulations and field observations.

OBJECTIVES

The specific objectives of this project are to:

- Derive a complete set of fully nonlinear Boussinesq-type equations for waves and currents over a permeable beach, including the swash zone, and simulate waves propagating over heterogeneous porous beds.

- Extend the two-dimensional, phase-resolving Boussinesq wave model to the swash zone with an emphasis on alongshore swash motions.

- Integrate the extended model with field data to gain insight into alongshore swash currents, including the correlation between the swash motions and the energetic shear waves.

APPROACH

The study involves theoretical formulation, model development and verification, and integration with field observations of swash motions. The starting point of the theoretical formulation is the Euler equation of motion for waves and currents above the permeable seabed and the locally-averaged Navier-Stokes equations for the flow inside the porous layer. A complete set of fully nonlinear Boussinesq-type equations for waves and currents over a permeable beach is developed. Particular attention is paid to the conservation property of potential vorticity and the poor performance of pre-existing equations when the ratio of the porous layer thickness to the water depth is large. Stokes-type analyses are carried out to examine the dispersion and damping properties of the new set of equations.

In order to simulate nonlinear wave propagation over heterogeneous porous beds, it is desirable to solve the new set of Boussinesq equations using higher-order numerical methods. One of the numerical problems associated with the simulation of swash motions is the requirement of very fine resolution in the swash zone in order to resolve the steep bore front and to prevent numerical instabilities caused by the moving shoreline. A conventional rectangular grid mesh covering a littoral area usually has difficulty to provide enough resolution in the surf and swash zone because of the computational

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restraint. One of the solutions to the resolution problem is to transform the Boussinesq equations derived in a Cartesian coordinate system to the generalized curvilinear coordinates, as shown in Shi et al. (2001). The transformation allows for varying the grid spacing to give fine enough resolution in the swash zone and avoid over-resolving waves in the deep water. Furthermore, the small grid spacing in the swash zone permits the use of the wetting-drying method on a fixed grid for the treatment of a moving boundary. A comparison of different schemes for the moving boundary in the Boussinesq model is carried out to determine the optimum technique with both good accuracy and efficiency for simulating cross-shore and alongshore velocities in the swash zone.

A close collaboration and interaction with field-oriented researchers on swash zone processes is one of the important components of this project. Field data collected by Dr. Britt Raubenheimer's research group at the Woods Hole Oceanographic Institute (WHOI) and Dr. Todd Holland's research group at the Naval Research Laboratory (NRL) will be utilized to verify the Boussinesq model with respect to wave runup and swash motion on beaches. The datasets include in-situ sensor array measurements and video-based observations. The verified Boussinesq model capable of simulating the swash motion on irregular beach topography will become available for the collaborators to study alongshore swash zone currents and allow for the development of hypotheses to be evaluated in future field experiments.

WORK COMPLETED

First, we have derived a new set of Boussinesq-type equations for nonlinear waves and surf-zone currents over a permeable beach (Chen 2006). A Stokes-type analysis and rational expansions have been carried out to examine the fundamental damping and dispersion properties of the new set of equations (Cruz and Chen 2006a). The vortical properties of the new and pre-existing Boussinesq equations have been carefully investigated. Second, numerical implementation of porous effects into a one-dimensional Boussinesq wave model has been completed. Preliminary results were documented in Cruz and Chen (2004). We have tested the numerical model against laboratory experiments on wave transformation over heterogeneous porous beds and submerged rubble mounds. The results have been published in Cruz and Chen (2006b). Third, efforts have been devoted to the testing of the curvilinear Boussinesq wave model, FUNWAVE 2.0, with respect to swash motions. We have examined three different schemes for the treatment of a moving shoreline with an emphasis on the swash velocity. Tests of the improved FUNWAVE model against analytical, laboratory and field data of swash and surf zone currents have been carried out (Chen and Briganti 2006). Fourth, Lagrangian descriptions of the fluid motion have been employed to study the mixing of surf zone currents, which serves as an alternative to Eulerian analyses of the flow field (Briganti et al. 2006).

RESULTS

The major results obtained so far are: 1) the development of a complete set of Boussinesq-type equations suitable for water waves and wave-induced nearshore circulation over an inhomogeneous, permeable seabed, 2) the implementation and testing of the new numerical model, namely PFUNWAVE 1D, 3) the implementation and testing of numerical schemes for the simulation of alongshore swash currents, and 4) numerical simulations of surf and swash zone currents under field conditions. We have developed a new approach to eliminating the ambiguity of the vertical voritcity component in Boussinesq-type wave equations. This technique allows for the existence and advection of the vertical vorticity component in the surf and swash zone currents with the accuracy consistent with the level of approximation in the Boussinesq-type equations for the pure wave motion.

Pre-existing Boussinesq-type equations perform poorly when the thickness of the porous layer is several times lager than the water depth. We reexamined the scaling of the resistance force and revealed the significance of the vertical velocity to the pressure field in the porous layer. This led to the retention of higher-order terms associated with the damping in the momentum equations. An analysis of the vortical property of the resultant equations indicates that the energy dissipation in the porous layer can serve as a source of vertical vorticity up to the leading order. The equations retain the conservation of potential vorticity up to $O(\mu^2)$, where μ is the measure the frequency dispersion. Such a property is desirable for modeling wave-induced surf zone currents. Moreover, the procedure of consistently recovering the vertical vorticity and eliminating the z-dependency can be used to extend a variety of Boussinesq-type equations originally derived for potential flows to quasi-rotational wave-current motions in the nearshore (Chen 2006).

A Stokes-type analysis and rational expansions were carried out to extract the fundamental properties from the complex Boussinesq equations. The linear dispersion relationship and the damping rate owing to the porous layers were compared with the exact solutions for linear waves over a homogeneous, porous, flat bottom (Cruz and Chen, 2006a). We developed a new optimization technique to determine the two model parameters for the new equations (Cruz and Chen, 2004). The new procedure has been extended to realistic bottom topography, allowing for variations of the model parameters to account for spatial variations of bottom permeability and porous-layer thickness.

We developed a new Boussinesq model for nonlinear waves propagating over porous beds (Cruz and Chen 2006b). The numerical model was tested against the analytical solution of linear waves on a horizontal, homogenous porous bed. Excellent agreement has been found. To verify the model accuracy for nonlinear waves propagating over uneven porous beds, the model was further tested using laboratory data. Figure 1 shows the computed special profiles, wave heights, and comparison of modeled and measured time profiles of waves over an underwater gravel mount. The solid lines in the bottom panels are the model results (Cruz and Chen 2006), while the symbols are the measurements from Hsiao et al. (2002). It is seen that PFUNWAVE simulates well the shape and magnitude of time profiles at most of the 9 stations, although there are deviations in the last three gages. The new numerical model has the potential to model nonlinear waves over heterogeneous porous beds.

The fully nonlinear Boussinesq model on generalized curvilinear coordinates, FUNWAVE 2.0, is a component of the nearshore modeling package, NearCoM. We have adopted FUNWAVE as the platform for modeling alongshore swash currents. Three numerical schemes for the treatment of a moving shoreline have been tested in the framework of FUNWAVE 2.0. They are the slotted-beach technique for wave runup, the thin-film method used in coastal ocean and estuarine circulation models for the treatment of tidal flats (Oey 2005), and the wetting and drying scheme using linear extrapolation (Lynett and Liu 2002). It turns out that the current version of FUNWAVE 2.0 incorporating the slotted-beach is not able to correctly model the swash velocity owing to numerical instabilities when small slot width or film thickness is used. A better-devised numerical filtering scheme is needed to stabilize the narrow slotted-beach scheme in the swash zone.

We have tested the 1D model using the analytical solution of long wave runup on a sloping bottom (Carrier and Greenspan, 1958). Good agreement has been found for the case of using the wetting and drying technique. Extension of the swash scheme to two horizontal dimensions with periodic cross-shore boundary conditions for the simulation of alongshore currents has been made. Figure 2 shows the comparison of the numerical and exact solutions of wave resonance in a parabolic basin.
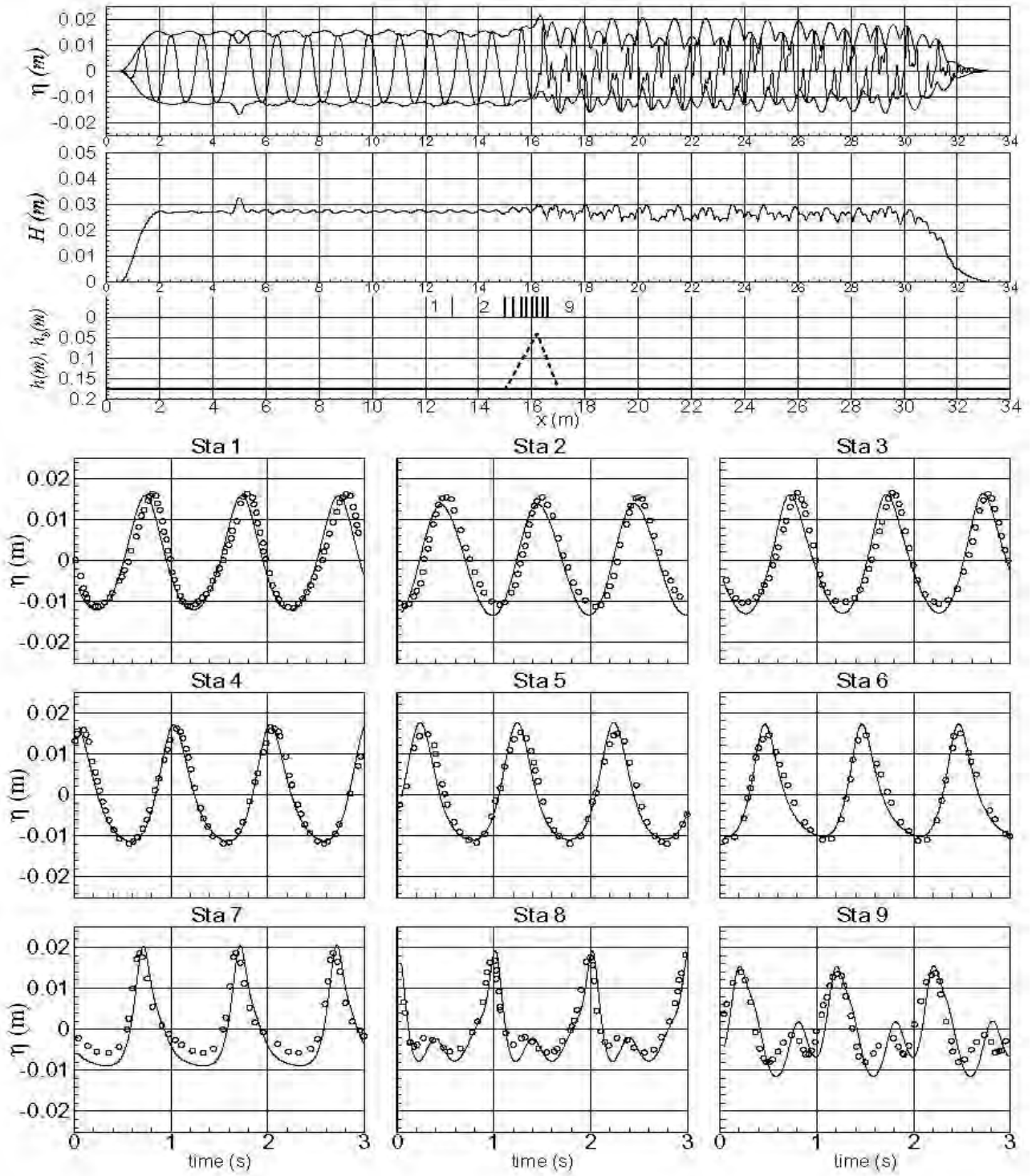
Figure 1: Special profiles, wave heights, and comparison of modeled and measured time profiles of waves over an underwater gravel mount. Solid lines: model results (Cruz and Chen 2006); Symbols: measurements (Hsiao et al. 2002).
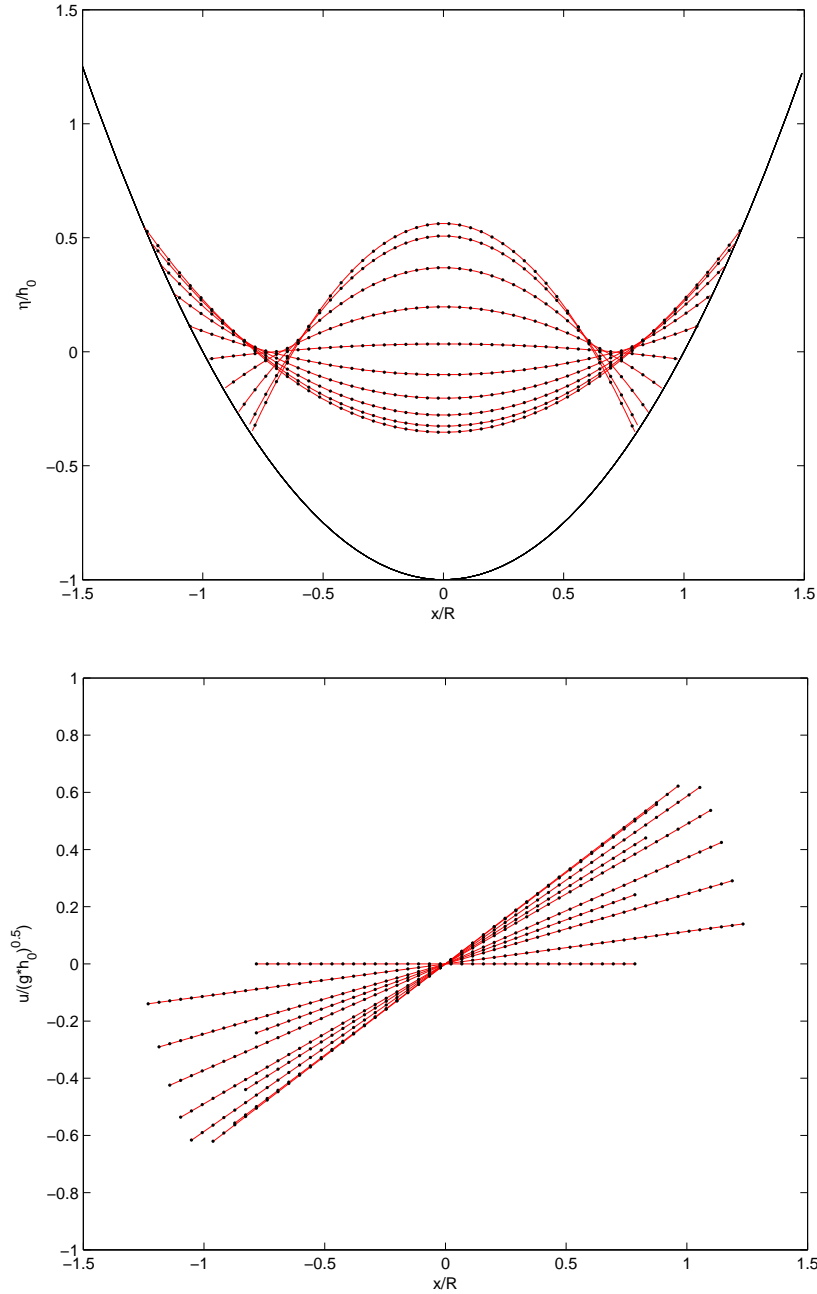
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Figure 2: Comparison of the numerical and exact solutions of wave resonance in a parabolic basin. Top: surface profiles, bottom: velocity profiles. Red lines: model (Chen and Briganti 2006); Dots: analytical solution (Thacker 1981).

It is seen in Figure 2 that the improved Boussinesq wave model with the wetting and drying scheme is able to accurately reproduce the analytical solution of both surface and velocity profiles given by Thacker (1981). Testing of the model against the laboratory experiment on the runup of a solitary wave on a conical island was also carried out and generally good agreement has been found (Chen and Briganti 2006). The model is being further tested against the latest analytical solution of the swash

motion (Antuono, Brocchini and Grosso 2006) with respect to the capability of predicting the alongshore drift velocity in the swash zone.

Considerable efforts have been devoted to the simulations of surf and swash zone currents measured during the SandyDuck and NCEX field experiments using the improved Boussinesq wave model. It turned out that FUNWAVE 2.0 in generalized curvilinear coordinates was not able to model the transport of the vertical vorticity component generated by wave breaking. Therefore, all the field applications have been carried out using the improved Cartesian version of FUNWAVE 2D.

Figure 3 illustrates the time sequence of the velocity and vertical vorticity fields predicted by the improved Boussinesq wave model (Chen and Briganti 2006) under the SandyDuck field conditions. The solid lines are the contours of water depth and the shoreline is on the left. We notice that the wetting and drying scheme handles the moving shoreline and swash motion fairly well in terms of numerical instabilities and mean longshore currents.
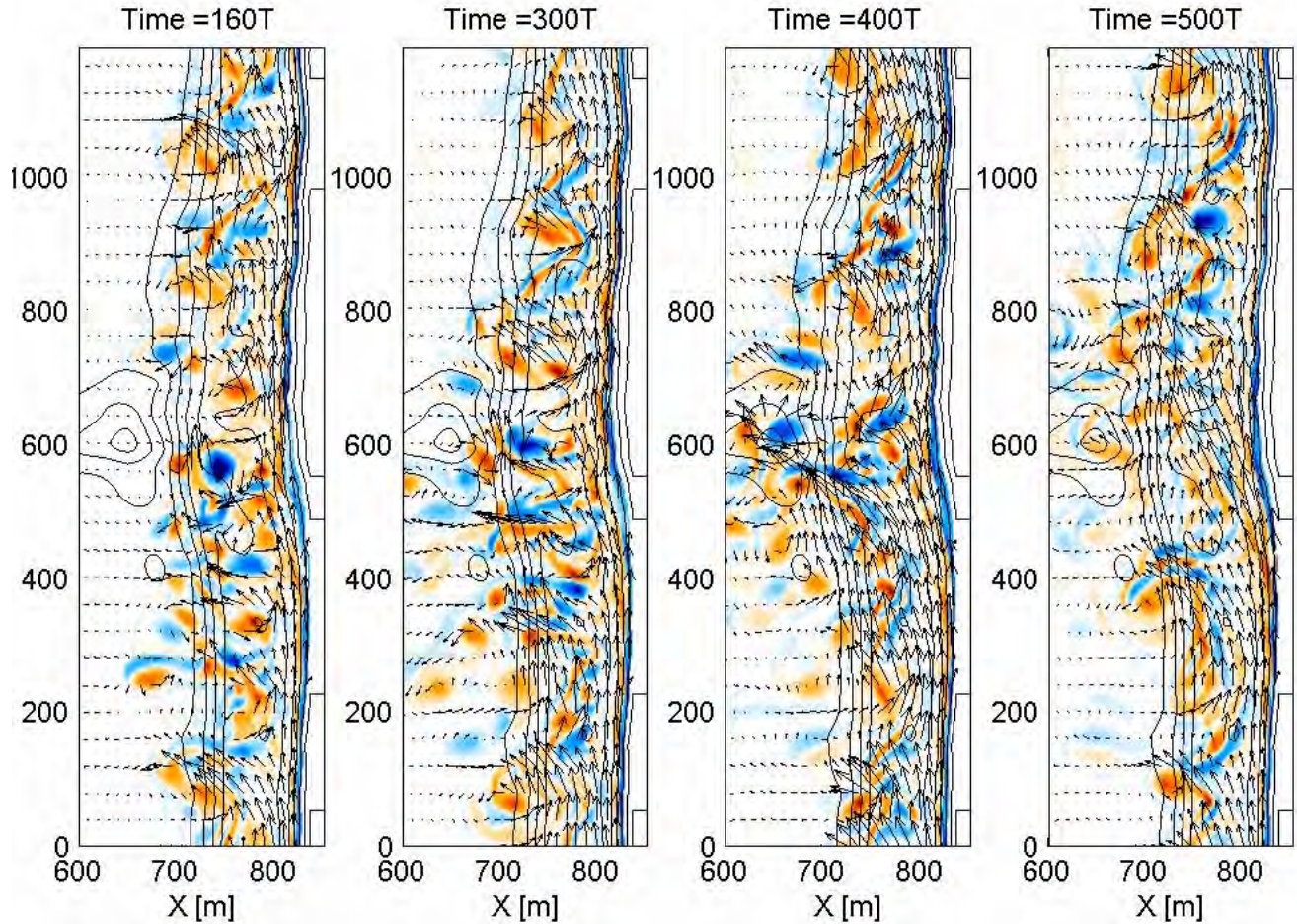

Figure 3: Time sequence of the velocity (vectors) and vertical vorticity (colors) fields predicted by the improved Boussinesq wave model (Chen and Briganti 2006) under the SandyDuck field conditions. The solid lines are the contours of water depth. The shoreline is on the left.

Detailed comparisons with the field data of SandyDuck and NCEX are being carried out. In addition to the theoretical and numerical results summarized above, we have utilized a particle tracking technique to examine the Lagrangian particle statistics of the flow fields produced by three sets of Boussinesq-type equations implemented in the FUNWAVE 2D, including the equations developed in this project by Chen (2006). Figure 4 shows the time sequence of the particle trajectories inferred from the output of the improved Boussinesq wave model under the SandyDuck field conditions (Briganti et al. 2006). The solid lines represent the contours of water depth and the shoreline is on the left.

A cluster of weightless particles were seeded shoreward of the sand bar crest a t=0. The particles were transported and dispersed by the surf zone currents generated by wave breaking. Owing to the cross-shore currents, a number of the particles were transported outside the surf zone at the early stages of the simulation and through the bottom depression under the research pier. Once they were outside the surf zone, the particles moved very slowly because of the weak currents. It is seen that only a potion of the cluster remains in the bar trough where they were transported by the strong longshore current. The particle tracking technique serves as an alternative to conventional Eulerian descriptions of surf zone currents. Particle statistics are being computed to examine the mixing properties of longshore currents predicted by phase-resolving and phase-averaged nearshore circulation models (Briganti et al 2006).
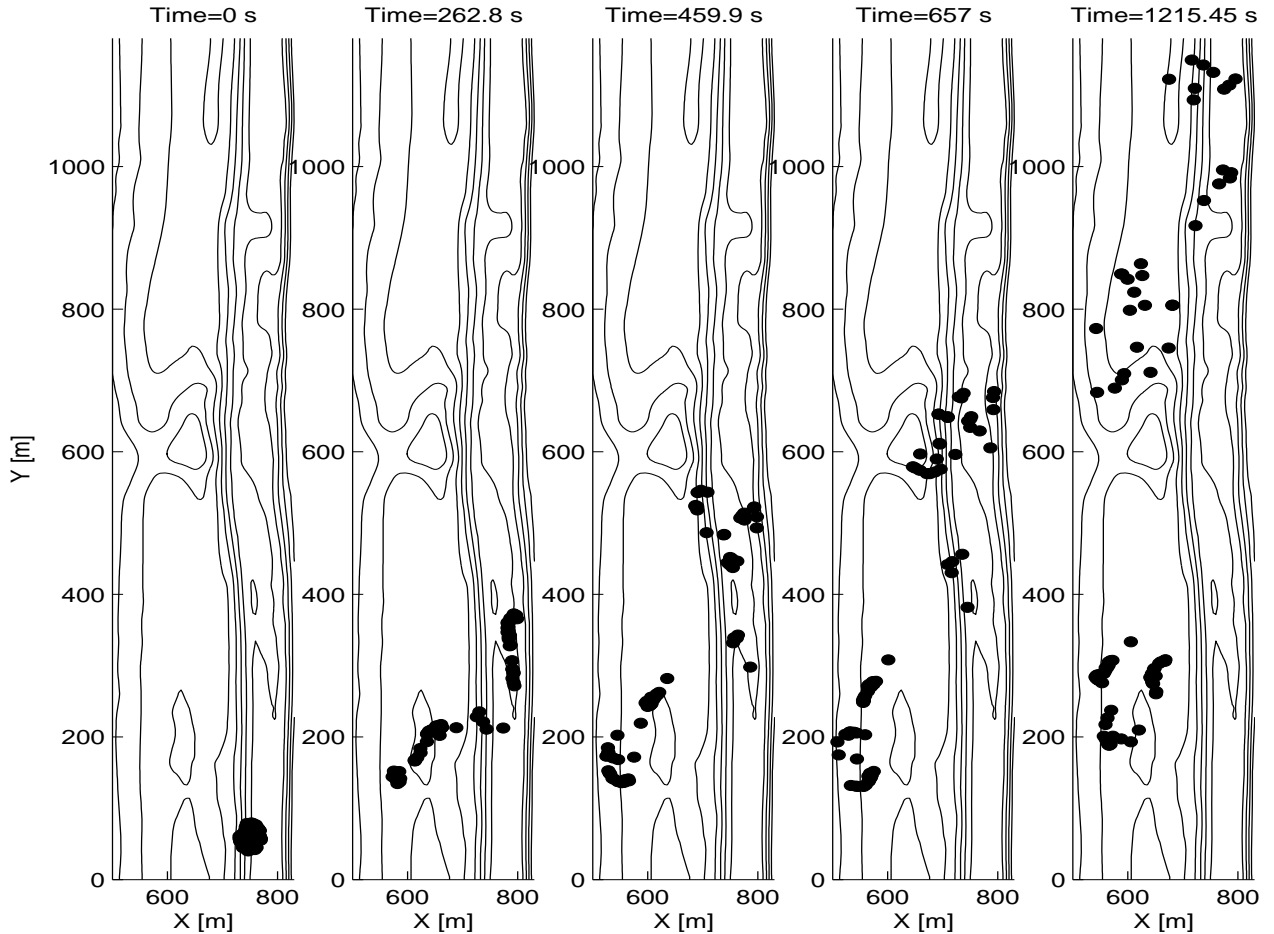

Figure 4: Time sequence of the particle trajectories inferred from the output of the improved Boussinesq wave model under the SandyDuck field conditions (Briganti et al. 2006). The solid lines represent the contours of water depth and the shoreline is on the left.

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IMPACT/APPLICATIONS

The present research is expected to improve the Navy's capability of modeling swash zone processes. First, the study extends the applicability of Boussinesq models (Chen et al., 1999, and Chen et al., 2003) to the swash zone and permeable beds. This will provide sediment transport models with more realistic estimates of cross-shore and alongshore velocities in the swash zone. Therefore, improvements in predicting sediment transport in the swash zone are anticipated. Second, the complex nature of nearshore processes calls for the integration of numerical models with field measurements in our research. The extended model will become available for researchers at the NRL and other institutions to complement their field study of swash zone processes, including alongshore swash zone currents measured in the NCEX. In addition, the project has also complemented the NOPP project led by Dr. Jim Kirby to develop and verify a community model for nearshore processes. The phase-resolving Boussinesq model with extension to the swash zone provides the phase-averaged wave and current models developed in the NOPP project with useful information about the swash motion and the shoreline boundary conditions. The results will give new insight into alongshore swash zone currents. In addition, the Boussinesq model for irregular waves propagating over porous beds is useful for the MURI study on remote sensing of seabed properties.

TRANSITIONS

The complete set of Boussinesq equations for nonlinear waves and surf zone currents has been shared with the NOPP researchers. As a result, the second-order vertical component of the vorticity vector on an impermeable bed has been implemented into the Boussinesq wave model, FUNWAVE, at the University of Delaware. In addition, Dr. Michael Strand at the Naval Surface Warfare Center has expressed strong interest in the Boussinesq models for wave transformation on a heterogeneous porous seabed.

RELATED PROJECTS

The field observations of cross-shore and alongshore swash-zone fluid velocities by Dr. Britt Raubenheimer at the WOHI are utilized to verify our numerical models.

Dr. K. Todd Holland at the NRL is leading the study of nearshore processes on heterogeneous beaches. Integration of our models with his field observations is planned.

ONR had recently released a BAA of a MURI dealing with the inversion of free surface information to infer the bottom sediment composition. The Boussinesq wave model extended to porous beds can be used to complement the study.

The development of the numerical models has been partially supported by the Federal Highway Administration through the study of storm wave transformation over inundated coastal roadways.

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